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1 **MONITORING LANDFILL COVER BY ELECTRICAL RESISTIVITY**  
2 **TOMOGRAPHY ON AN EXPERIMENTAL SITE**

3

4

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14

15 **Abstract**

16 In France, the monitoring of landfill cover after closure of the site is a local problem, since its  
17 tightness must be ensured over time. Leaks in the cover are a problem, as they allow water to  
18 infiltrate the stored waste. In order to locate such leaks, electrical resistivity tomography was  
19 used on an experimental site in which defects had been intentionally made in the cover.  
20 Repeated measurements taken on this site showed that the weather conditions preceding the  
21 measurements need to be taken into account, as they affect the water content in the cover  
22 material. They also showed that there are optimal weather conditions for detecting defects in  
23 the cover. A statistical analysis carried out on the electrical resistivity results for all surveys  
24 and cover material samples showed that the material was heterogeneous; this variability was  
25 mainly due to a difference in particle size (fines content) and in compaction.

26 This study has shown the capacity of electrical resistivity tomography to detect defects and  
27 heterogeneity in the cover material, indicating that it is a good means of monitoring the  
28 quality of landfill cover both when it is put in place and subsequently.

29

30 Keywords: landfill cover, gravelly clay material, heterogeneity, compaction, electrical  
31 resistivity, multivariate analysis

32

### 33 **1. Introduction**

34

35 In France, the management of household waste is a local problem regarding the  
36 quantities of waste produced each year. Nearly half of it is stored in Municipal Solid Waste  
37 Landfills (MSW). These sites consist of several cells which are covered once they are full of  
38 waste. On its edges, this cover must have a slope of around 3% to facilitate water runoff. The  
39 law of 9 September 1997, published in the French *journal officiel* on 2 October 1997, made it  
40 obligatory to cover landfill so as to limit the infiltration of water into the waste; there is also  
41 an economic aspect, since the cost of treating leachates is high. The law was modified by the  
42 orders of 31 December 2001, 3 April 2002, 19 January 2006 and 18 July 2007. However,  
43 there are no French regulations concerning the composition of the cover. It is simply  
44 recommended to use clayey material which may be associated with geosynthetics  
45 (geomembranes or Geosynthetic Clay Liners), depending on the date of closure (Silvestre et  
46 al., 2003; ADEME, 2001). Over time, mechanical, climatic and hydraulic constraints may  
47 induce leaks in the cover. Indeed, the cover can be damaged during its installation. It is  
48 important to locate the damaged areas as they can cause an increase in the quantity of  
49 leachates in times of rain.

50           Being non-destructive, geophysical methods could be a good way of detecting these  
51 anomalous zones. The use of electrical methods seems interesting for investigating the cover  
52 of landfills containing non-hazardous waste, for which few studies have been undertaken  
53 (Carpenter et al., 1991; Guyonnet et al., 2003; Ait Saadi, 2003). The electrical resistivity of a  
54 soil is a function of many properties (a synthesis of which was presented by Samouëlian et al.  
55 (2005)) such as compaction (Abu-Hassanein, 1996; McCarter, 1984), water content  
56 (Schwartz, 2008) and density of the material (Cosenza et al., 2010; Seladji et al., 2007;  
57 Besson et al., 2004) as well as temperature (Blewett, 2003; Rein et al., 2004; Hayley et al.,  
58 2007).

59           In order to study the behaviour of a loamy-clay cover material, an experimental site  
60 was established in which the effect of ageing was intentionally simulated through defects in  
61 the cover. The aim of our study was to test the ability of electrical resistivity methods to  
62 detect these defects and to characterise the heterogeneity of the cover material.

63           After the description of the study site, the electrical resistivity methods used to  
64 characterise the cover material are presented. The influence of the meteorological conditions  
65 (temperature and precipitations) was taken into account through the continuous recording of  
66 weather data near the site, as well as humidity and temperature data at various depths in the  
67 cover. Finally, the electrical resistivity models for the various surveys undertaken on the  
68 experimental site are presented. After observation of the varied behaviour of the cover, we  
69 carried out multivariate analysis on the electrical resistivity data of the gravelly-clay material.  
70 Finally, samples taken from the cover are described and interpreted.

71

72

## 73       **2. Material and methods**

74

75           2.1 Presentation of the experimental site

76

77           An experimental site was excavated with the aim of studying the behaviour of a  
78 landfill cover made up of 0.15 m of topsoil and one metre of reworked clayey material (Figure  
79 1). The material was brought in from the town of Touvre en Charente (France), some 10 km  
80 distant, and had been excavated two months before being transported to the site. The material  
81 consisted of ancient alluviums made up, essentially, of silts and brown plastic clays.  
82 Laboratory tests such as methylene blue adsorption test (index about 5.5) and Atterberg limits  
83 (plasticity index  $I_p \approx 11\%$ ) confirmed the loamy-clay nature of the material samples taken  
84 with the hand auger. However, the non-samplable sand and gravel observed *in-situ* lead us to  
85 qualify the material as gravelly clay, according to the GTR classification (NF P 11-300).

86           The material was put in place in three stages: the first layer of 40 cm and two other  
87 layers of 30 cm (referred to as Layer 1, Layer 2 and Layer 3 respectively in Figure 1). The  
88 experimental site was excavated in loamy alluvium, except for the north-west and south-east  
89 extremities, where the bedrock was backfilled (Figure 1). The material of each layer was  
90 levelled using the scoop of a 9-ton mechanical digger and then compacted by the caterpillar  
91 tracks of the mechanical digger as it was driven over the whole surface. The site building  
92 conditions have unfortunately not allowed to perform Proctor tests on the gravelly clay  
93 material. Moreover, because of the small size of the experimental site, the recommended  
94 slope of the cover has not been created. As the layers of gravelly clay material were put in  
95 place, so were cracks and material generally used for geodrains in landfill sites (Figure 1).

96

97           The three 2.5 m-long cracks went through the thickness of the gravelly clay material  
98 cover, from -0.15 to -1.15 m (Figures 1 and 2). They were made to simulate a construction  
99 defect or the consequences of deterioration by shrinkage and swelling of the cover material or

100 by differential settling. The 4 and 10 cm-wide cracks were filled with sand. Two geodrains,  
101 G1 and G2, 8 mm wide and with an area of approximately 1 square metre, were placed, one  
102 after the first layer of the cover was put in place, the other after the second layer (Figures 1  
103 and 2).

104

105         Moisture probes (FDR type thetaprobes) and temperature probes (PT100) were also  
106 installed as the site was established (Figure 2) to record humidity and temperature over time.  
107 The site building conditions made it necessary to develop a procedure for correcting the  
108 moisture measurements after probes were put in place. As the hydric conditions of the cover  
109 material were constant during the 11 days between the beginning of recording on the  
110 9 October 2009 and the first rain, it was estimated that the curves would be superimposed  
111 during this dry period. The *a posteriori* procedure was thus to check the consistency of each  
112 of the four curves during this period and to superimpose them, taking, as reference, the curve  
113 with values that corresponded to the humidity measurements taken in the laboratory on a  
114 given date.

115         A weather station was set up near the site so as to record the meteorological conditions  
116 (precipitations, atmospheric temperature, etc.). Evapotranspiration was also recorded at the  
117 station.

118

119

## 120         2.2 Measurements by electrical resistivity tomography

121

122         Since the site was set up in September 2009, six surveys using electrical resistivity  
123 tomography have been carried out using the Syscal Pro (IRIS Instruments) resistivity meter  
124 with various arrays (Wenner, Wenner-Schlumberger, gradient and dipole-dipole). Here, we

125 present the results obtained using the dipole-dipole array, as it is the easiest to set up quickly  
126 on site, although the gradient array seemed more accurate. The ERT<sub>2</sub> profile (Figure 3),  
127 consisting of 48 electrodes placed at intervals of 0.50 m, crossed one of the two 10 cm-wide  
128 cracks perpendicularly and passed directly over geodrain G1 situated at a depth of 0.75 m. In  
129 order to eliminate any possibility of artefacts linked to the first measurements of the day, we  
130 took repeatable measurements by the successive acquisition of electrical resistivity data along  
131 the ERT<sub>2</sub> profile (Peter-Borie et al., 2011). These measurements were taken with the dipole-  
132 dipole array and did not present significant variation of electrical resistivity between the first  
133 measurements of the day and the following, allowing the measurements to be taken more  
134 quickly.

135         Measurements on other profiles were also taken over the whole site; the results were  
136 comparable to those of ERT<sub>2</sub> (Genelle et al., 2010; Genelle et al., 2011) and are not presented  
137 here. A “control” line, ERT<sub>c</sub>, (Figure 3) was set up on 8 February 2011, 1.20 m from ERT<sub>2</sub> in  
138 a zone with no anomalies; samples of gravelly clay material were then taken along this profile  
139 in order to characterise its heterogeneity without affecting the site around the anomalies.

140

141         The apparent electrical resistivity of the various surveys was inverted with the  
142 RES2DINV© software by means of a robust inversion (Loke et al., 2003) and model  
143 refinement. The resistivity models resulting from the inversion are presented as blocks. The  
144 true resistivity located in the cover were then corrected for temperature thanks to the data  
145 from the sensors on the experimental site (Figure 2). The position of these sensors make it  
146 possible to take into account the variation of temperature against depth; they were placed at  
147 depths of 0.10 and 0.15 m in the topsoil (sensors 5 and 6 in Figure 2) and at 0.35 and 0.70 m  
148 in the gravelly clay material (sensors 7 and 8 in Figure 2). We assumed that the temperatures

149 recorded at each depth, far from any defect, would be representative of those in the whole  
150 material (top soil and gravelly clay) at the same depth.

151 Concerning the correction for temperature, various models allow the electrical  
152 resistivity values recorded at temperature  $T$  (denoted as  $\rho_T$ ) to be adjusted to the reference  
153 temperature of  $25^\circ\text{C}$  (denoted as  $\rho_{25}$ ) (Ma et al., 2010). The correction factor  $f_T$  can be  
154 expressed by means of various functions: linear (Campbell et al., 1948), exponential (Sheets  
155 and Hendrickx, 1995; Lück et al., 2005; Corwin and Lesch, 2005) and power (Besson et al.,  
156 2008). Ma et al. (2010) compared these various expressions of the correction factor to  
157 measurements of electrical resistivity taken at various temperatures on soil samples and  
158 published in the Agriculture Handbook n°60 (US Salinity Laboratory Staff, 1954). The  
159 expression  $\rho_T = f_T \times \rho_{25} = [0.4470 + 1.4034 \times \exp(-T/26.815)] \times \rho_{25}$ , established by Corwin  
160 and Lesch in 2005, is the one for which the residues calculated in relation to the data in the  
161 Agriculture Handbook, for temperatures of between  $3$  and  $47^\circ\text{C}$ , are the lowest. So, it is this  
162 expression that is used here to correct the values of electrical resistivity.

163

### 164 2.3 Monitoring precipitations, atmospheric temperature and humidity

165

166 Study of the electrical resistivity measured over time on the experimental site required  
167 the current and preceding meteorological conditions to be taken into account. The data for  
168 effective rain (Figure 4. a) and atmospheric temperature (Figure 4. b) allow the classification  
169 of the surveys undertaken on the site according to the local meteorological conditions. To  
170 facilitate the use of these figures, the date of each geophysical survey is indicated in Figure 4  
171 by a black line.

172



173 According to the hydric conditions and temperature observed during the six surveys,  
174 the measurements were classified in two periods, wet and dry. The wet period measurements  
175 were those taken on 2 and 10 February and 19 November 2010, when the rainfall  
176 accumulation was 60.3 mm in the month of January and 90.0 mm for the period 1 to  
177 18 November 2010. These high levels of precipitations were linked to low atmospheric  
178 temperature, on average 2.8 °C during the surveys from 2 to 10 February and 8.4 °C during  
179 the survey of 19 November 2010.

180 The meteorological conditions observed at the time of the measurements taken in  
181 September 2010 differ from those of the three preceding surveys. During July, August and  
182 September, atmospheric temperatures were high (the monthly averages were respectively  
183 21.8 °C, 19.6 °C and 16.5 °C) and there were negative effective rainfall accumulations  
184 (respectively -113.3 mm, -88.8 mm and -64.0 mm). This absence of effective rain led to a  
185 decrease in humidity in the gravelly clay material. The volumetric water content during the  
186 dry period at the time of this survey was  $0.20 \text{ m}^3 \cdot \text{m}^{-3}$  at a depth of 0.70 m (Figure 4 c.). This  
187 value contrasts with the higher one recorded during the wet period ( $0.26 \text{ m}^3 \cdot \text{m}^{-3}$  -  
188 corresponding to a humidity variation of 30%).

189 The February 2011 measurements were taken in intermediary hydric conditions,  
190 between those of the two preceding periods. The humidity of  $0.25 \text{ m}^3 \cdot \text{m}^{-3}$  at a depth of 0.70 m  
191 was lower than that of February 2010. This value represents a reduction of about 4% and is  
192 linked to a rainfall accumulation that was four times lower in the month of January 2011  
193 (15.8 mm) than in the preceding year (60.3 mm).

194 Although the volumetric water content of the gravelly clay material during the survey  
195 of 8 February 2011 was similar to that of 22 October 2009 ( $0.23 \text{ m}^3 \cdot \text{m}^{-3}$ ), these two surveys  
196 have to be studied separately. The October survey occurred after a single fall of rain (19.3 mm  
197 on 20 September 2009) which took place after the experimental site was established, while the

198 February 2011 survey took place after a series of episodes of light rain (on average, 2 mm per  
199 day) with an accumulation of effective rain of 3.6 mm one month before the survey.

200

#### 201 2.4 Qualification of the initial state of the experimental site

202

203 After each of the three layers of gravelly clay material was put in place, electrical  
204 mapping was carried out using 2 m mesh made up of six parallel lines arranged in a north-  
205 west south-east direction. The measurements were taken with a Schlumberger array  
206 ( $AB/2=0.50$  m and  $MN/2= 0.10$  m) thanks to a device developed by HYDRO INVEST.  
207 Between the 8 and 14 September 2009, the cover material was put in place and the resistivity  
208 measurements were taken.

209 The measurements of apparent electrical resistivity were then inverted on the basis of a  
210 two-layer model in which the true resistivity of the alluvium and subjacent anthropogenic  
211 deposits (Figure 1) were known thanks to an electrical resistivity tomography profile  
212 established on the excavated area before the cover was put on. The values of true resistivity  
213 obtained with the formula of Bhattacharya and Patra (1968) were corrected for the effect of  
214 temperature on the assumption that the measurements had been influenced by atmospheric  
215 temperature alone (the average value of the atmospheric temperature data from the  
216 meteorological station near the site between the 4 and 21 September 2009). The gravelly clay  
217 material was considered to be in equilibrium with the atmospheric temperature, the excavation  
218 and storage having been done two months previously. With these data, iso-resistivity maps  
219 were established for each of the three layers of material at the moment that they were put in  
220 place. These maps were the result of interpolation by kriging with a search ellipse radius of  
221 4 m using the SURFER software. One of the maps is presented in Figure 16; it is based on

222 kriging interpolation with an exponential and quadratic model fitted to the omni-directional  
223 experimental variogram.

224

225

### 226 **3. Results**

227

#### 228 3.1 Detection of the 10 cm-wide crack

229 The models of electrical resistivity for the ERT<sub>2</sub> profile (Figure 5) presented values of  
230 electrical resistivity that were not corrected for the effect of temperature during the six series  
231 of measurements from October 2009 to February 2011. The range of electrical resistivity on  
232 the site and its bedrock varied, overall, between 10 and 113 Ω.m. On each profile except that  
233 of September 2010 (Figure 5. d.), there were two large areas: one was superficial and  
234 conductive (electrical resistivity lower than 50 Ω.m) and the other was deep and resistive  
235 (electrical resistivity between 50 and 113 Ω.m). The boundary between these two areas along  
236 ERT<sub>2</sub> was located at a distance of between 2 and 17.5 m and a depth of 1.15 m; it continued  
237 beyond 17.5 m, gradually rising to the surface as the cover became shallower. So, this change  
238 in electrical resistivity took place at a depth corresponding to the total thickness of the  
239 experimental cover. The conductive area was thus that of the gravelly clay material and the  
240 resistive area that of the bedrock (Figure 1). Also, we observed, on all the models of electrical  
241 resistivity, a decrease in resistivity in the bedrock between 3 and 6 m. The decrease in the  
242 resistivity for the measurements with the dipole-dipole array was not found in the results  
243 achieved with the other arrays. We therefore suppose that it was caused by an artefact  
244 introduced when inverting the measurements taken by the dipole-dipole array; the artefact  
245 was verified by forward modelling. There was also a significant increase in electrical  
246 resistivity at a distance of about 4 m along the profile, except for that of September 2010

247 (Figure 5.d), over a thin slice through the entire thickness of the cover. This increase in  
248 resistivity appeared at the 10 cm-wide crack that was filled with sand (Figure 3). This  
249 resistivity of more than 100  $\Omega$ .m can thus be interpreted as being the signature of the crack,  
250 below 0.15 m of top soil. For deeper cracks, forward modeling computed with the  
251 RES2DMOD© (Loke, 2002) software have shown that electrical resistivity tomography  
252 would be able to detect these cracks (not shown here).

253 The 10 cm-wide crack was, however, not easily detected on the resistivity model for  
254 September 2010 (Figure 5. d) which presented, for the central part of the cover material,  
255 higher electrical resistivity (between 30 and 113  $\Omega$ .m). The contrast of resistivity between the  
256 crack and the rest of the cover was no longer perceptible with the range of electrical resistivity  
257 used; nevertheless, the true electrical resistivity at the place of the crack raised about  
258 600  $\Omega$ .m.

259 The presence, on the surface, of electrical resistivity greater than 80  $\Omega$ .m (Figure 5. d)  
260 should be seen in the light of the high atmospheric temperatures recorded during the summer  
261 (Figure 4.b.) which helped to dry the ground. Indeed, many cracks caused by drying, some of  
262 which were at least 36 cm deep, were observed during dry periods. These cracks no longer  
263 appeared during the later surveys undertaken during the wet period.

264 Apart from the September 2010 survey, the analysis of electrical resistivity not  
265 corrected for temperature for all the surveys led to the detection of the 10 cm-wide crack.  
266 Moreover, spatial variations in electrical resistivity within the gravelly clay cover were  
267 detected and seemed to persist over the course of the surveys. So, in order to characterise as  
268 well as possible this variability, it was necessary to correct the electrical resistivity for the  
269 effect of temperature in order to make the models comparable.

270

271 3.2 Electrical resistivity of the gravelly clay material : spatial organisation

272 Once the values were corrected, they were found to be between 10 and 40  $\Omega\cdot\text{m}$  (Figure 6)  
273 except for those of September 2010; a detailed examination revealed a spatial organisation  
274 that persisted from one ERT to the next.

275 As from the measurements taken in October 2009 (Figure 6. a.), one can see a spatial  
276 organisation of electrical resistivity along the ERT<sub>2</sub> profile. Three particularly conductive  
277 zones (A, B and C, with resistivity of between 10 and 20  $\Omega\cdot\text{m}$ ), were thus brought to light.  
278 The distribution of these low values of electrical resistivity was similar for the data acquired  
279 in wet periods (2 and 10 February and 19 November 2010, Figures 6 b., c. and e.). These  
280 zones nevertheless seemed smaller on 8 February 2011 (Figure 6 f.); this reduction in  
281 extension was linked to an increase in electrical resistivity in the superficial part of the cover  
282 material (between 0 and 0.25 m in depth). An analysis of precipitations over the seven days  
283 before 8 February 2011 shows that the effective rainfall accumulation was -2.8 mm, while in  
284 wet periods it was 6.5 mm on 2 February, 29.4 mm on 10 February and 27.1 mm on 19  
285 November 2010. The extension of zones A, B and C decreased from 2 February 2010 to 8  
286 February 2011; this was particularly obvious for zone A.

287 It is interesting to note the variations in electrical resistivity in the superficial part of  
288 the cover material in the measurements taken at a close interval, on 2 and 10 February 2010  
289 (Figures 6 b. and c.). The resistivity at between 5 and 20 m horizontal distance and to a depth  
290 of 0.25 m were lower for the measurements of 10 February 2010. The average of these values  
291 was 30.8  $\Omega\cdot\text{m}$  on 2 February (with a minimum of 17.7  $\Omega\cdot\text{m}$ ) and 26  $\Omega\cdot\text{m}$  on 10 February (with  
292 a minimum of 13.6  $\Omega\cdot\text{m}$ ). In fact, the precipitations' accumulation over the seven preceding  
293 days was different for each of these two surveys; it was 29.4 mm for the 10 February and only  
294 6.5 mm for the 2 February 2010. Consequently, the differences of electrical resistivity in the  
295 superficial part of the gravelly clay material could be, a priori, due to variations of humidity in

296 the cover, themselves linked to the precipitations preceding the measurements in a period that  
297 was generally wet.

298

299 We noted a certain consistency in the spatial distribution of electrical resistivity in the  
300 gravelly clay material, except in the month of September 2010. The change in electrical  
301 resistivity over time in the various zones depends on the frequency and intensity of  
302 precipitations preceding the measurements and, therefore, on the conditions of humidity at the  
303 time of the surveys.

304

### 305 3.3 Statistical analysis of electrical resistivity values

306 In order to quantitatively establish areas of similar electrical resistivity in the cover,  
307 we used multivariate analysis (ascendant hierarchical classification, ACH). The clustering of  
308 164 standardized variables of electrical resistivity at between 5 and 19 m and depths of  
309 between 0.26 and 0.76 m for the six series of measurements was done using the Ward linkage  
310 method together with a Euclidian distance measure. The electrical resistivity data for the  
311 blocks situated on the upper and lower levels of the gravelly clay material, as well as those of  
312 the four blocks situated at between 18 and 19 m and at a depth of 0.76 m were not taken into  
313 account because of the influence of the top soil on the surface and by the deeper, bedrock.  
314 ACH (Figure 7) permits the identification of four clusters of electrical resistivity values.

315

316 The dendrogram shows the distance level for each of the four clusters. First of all, one  
317 notes the greater proximity of clusters 2 and 3 which constitute 52% of the data at a distance  
318 of 25.22 (Figure 7). For clusters 1 and 4, the distance is greater (38.70), showing their greater  
319 variability. It is then possible to analyse by cluster and by date of measurement thanks to the

320 calculation of the statistical parameters, in particular the median and the standard deviation of  
321 the data (Table 1).

322

323 In order of increasing median values of electrical resistivity and for all dates of  
324 measurement, the clusters have the following order: 1-4-2-3. The values for clusters 1 and 4  
325 are the lowest: they vary, respectively, from 14.0 to 17.3  $\Omega$ .m and from 18.0 to 21.3  $\Omega$ .m in  
326 the wet period (Table 1). For clusters 2 and 3, the values were higher: they were, respectively,  
327 between 19.7 and 22.5  $\Omega$ .m and between 22.9 and 25.3  $\Omega$ .m in the wet period. The values  
328 confirm that clusters 2 and 3 are closer to each other than are clusters 1 and 4. Also, the ratio  
329 of the standard deviation to the median (Table 1) shows that the variations in electrical  
330 resistivity are of greater amplitude for clusters 1 and 3 than for clusters 4 and 2, in particular  
331 for the survey of September 2010. Cluster 1 contains the lowest, and cluster 3 the highest,  
332 values of electrical resistivity.

333

334 It is also interesting that the changes in the electrical resistivity of the four clusters  
335 develop in a similar way over time (Figure 8). Indeed, the resistivity reduces all the more  
336 when measurements are carried out during wet periods, with the exception of 22 October  
337 2009 (Figure 4 a.). For that date, the resistivity values cannot be considered as representative  
338 of the conditions of humidity in the material as the site had been established only one month  
339 before.

340

341 After the statistical analysis of the electrical resistivity of each of the four clusters, the  
342 study of their spatial distribution allows us to note, for each block, the cluster to which it  
343 belongs (for each of the six surveys) (Figure 9). The zones delimited by each cluster  
344 correspond overall to the previously identified zones A, B and C.

345

### 346 3.4 Heterogeneity characterisation of the gravelly-clay material

347 In order to determine the geotechnical characteristics of each of the four clusters,  
348 samples of material were taken along ERT<sub>c</sub>. Only the loamy clay component of the material  
349 could be taken with the hand auger. First, the clusters determined by ACH carried out on the  
350 data from ERT<sub>2</sub> were re-attributed to each of the blocks forming the resistivity model of  
351 ERT<sub>c</sub>. It was thus possible to compare the statistical parameters of ERT<sub>c</sub> profile to those of  
352 ERT<sub>2</sub> for the five series of measurements (Table 2); the values for September 2010 (a dry  
353 period) are not considered.

354

355 The median values of electrical resistivity of the four clusters for ERT<sub>c</sub> had the same  
356 hierarchy as for ERT<sub>2</sub>, cluster 1 having the lowest value (17.4 Ω.m) and cluster 3 the highest  
357 (22.6 Ω.m). We can also note that the deviation between the median values of electrical  
358 resistivity for clusters 2 and 3 was 1 Ω.m for ERT<sub>c</sub> and 2.8 Ω.m for ERT<sub>2</sub>.

359 In addition, the electrical resistivity of ERT<sub>c</sub> presents a ratio of standard deviation to  
360 the median which is lower than that of ERT<sub>2</sub>. Despite the differences observed in the  
361 statistical parameters of the two profiles, the electrical resistivity in ERT<sub>c</sub> (Figure 10 b.) had a  
362 similar spatial layout to that of ERT<sub>2</sub> (Figure 10. a.) on 8 February 2011. For example, they  
363 both present a low localised electrical resistivity in the 5 to 8 m zone.

364 The statistical and spatial analysis of electrical resistivity leads us to suppose, as a first  
365 approximation, that the electrical resistivity was, over time and as a function of the  
366 precipitation, identical for the two profiles.

367

368 The four samples of loamy clay material were taken from zones with values of  
369 electrical resistivity (Figure 10 b.) corresponding to the clusters defined by multivariate



370 analysis. Samples E<sub>1</sub> and E<sub>10</sub> correspond, respectively, to clusters 1 and 4, and E<sub>6</sub> and E<sub>14</sub> to  
371 clusters 3 and 2 (Figure 11).

372

373 In order to characterise the loamy clay material from each of the four samples,  
374 laboratory analysis was undertaken, to measure the gravimetric water content (Table 3) and to  
375 establish the particle size distribution curve (Figure 12) of each of the samples.

376 The values of gravimetric water content (Table 3) were found to be between 21.5 and  
377 28.0%. Samples E<sub>1</sub> and E<sub>10</sub>, having a water content of 28.0 and 26.5% respectively,  
378 corresponded to clusters 1 and 4. These two clusters presented the lowest electrical resistivity  
379 values (the median value of electrical resistivity for these two clusters was respectively 17.4  
380 and 19.7 Ω.m). For the other two samples (E<sub>14</sub> and E<sub>6</sub>), the gravimetric water content was  
381 respectively 21.5 and 23.5%. The samples came from zones attributed to clusters 2 and 3  
382 which presented median values of electrical resistivity of, respectively, 21.6 and 22.6 Ω.m.  
383 One sees here the inversion of electrical resistivity in relation to the values of gravimetric  
384 water content; this can be explained by the proximity of clusters 2 and 3 seen in the  
385 dendrogram (Figure 7).

386

387 The samples were then sieved in order to establish the particle size distribution curves  
388 (Figure 12). The curves show differences in the gravimetric percentage for fractions with a  
389 grain size of between 80 and 400 µm: the percentage of fines is seen to be greater than 80%  
390 for samples E<sub>1</sub> and E<sub>10</sub> and lower than 80% for samples E<sub>6</sub> and E<sub>14</sub>.

391 We can also note that the four gravelly clay samples characterised by different fines content  
392 are placed at the location of electrical resistivity variations on the ERT<sub>c</sub> model (Figure 13). It  
393 can also be noted that the proportion of fines in the loamy clay component of the material is in  
394 direct relation to the gravimetric water content (Figure 14).

395

#### 396 **4. Discussion**

397

398         The geotechnical parameters (gravimetric water and fines content) recorded for the  
399 samples can be studied in relation to the median values of the electrical resistivity of the four  
400 clusters in  $ERT_c$  (Figure 15). The graphs show that the median values of resistivity rise to an  
401 optimum peak and then decrease in direct relation to the gravimetric water content (Figure 15  
402 a.) and the percentage of fines (Figure 15 b.). However, taking into account the proximity of  
403 clusters 2 and 3, which are already visible in the dendrogram (Figure 7) and of the low  
404 deviation of electrical resistivity between these two clusters in  $ERT_c$  (Table 2), one can  
405 consider that the electrical resistivity tends to decrease with the content of gravimetric water  
406 and of fines. We will deal with the effect of compaction on electrical resistivity first, and then  
407 with that of the meteorological conditions.

408

409         The analysis of the samples has thus shown that the electrical resistivity of the  
410 different clusters is related to the heterogeneity of the cover material. This variability seems to  
411 be linked to both the gravimetric water content and the percentage of fines; and knowing that  
412 the electrical resistivity is also linked to compaction (Beck et al., 2008), we sought to  
413 demonstrate the effect of compaction while taking into account the intrinsic heterogeneity of  
414 the material. To do this, we used the map of electrical resistivity on the surface of layer 2  
415 (Figure 16). This map shows a central area of low resistivity (lower than  $30 \Omega.m$ ) and a  
416 peripheral area of more resistive material (most of the measurements of resistivity being  
417 between  $30$  and  $50 \Omega.m$ ). The differences in electrical resistivity can be put in relation to the  
418 effect of the mechanical digger: indeed, while the digger did pass regularly over the central  
419 area, this was not the case for the periphery of the site, where access was more difficult. So,

420 the lower values of resistivity could be linked to greater compaction. The differences in  
421 electrical resistivity revealed by the ERT imaging and in Figure 16 are similar: the resistivity  
422 of clusters 1 and 4 corresponds to a conductive zone of the map in Figure 16, while the  
423 electrical resistivity of cluster 2 corresponds to the resistive zone. Clusters 1 and 4, well  
424 individualised by the imaging, are thus well characterised by a finer particle size and a more  
425 obvious compaction. The coherence of the spatial distribution of the electrical resistivity, in  
426 the tomography imaging as well in the resistivity map (Figure 16), is due to both the intrinsic  
427 heterogeneity of the material and the effect of compaction.

428

429         Regarding the effect of precipitations on electrical resistivity, we present the  
430 monitoring of the volumetric water content over time at a depth of 0.70 m, 2 m north of ERT<sub>2</sub>  
431 profile (Figure 2). The monitoring of electrical resistivity along ERT<sub>2</sub> profile allowed us to  
432 relate decreasing median values of electrical resistivity of each of the four clusters to  
433 increasing volumetric water content (Figure 17). Even though the values of volumetric water  
434 content cannot be directly compared to the values of gravimetric water content of the samples,  
435 one can nevertheless see a tendency for electrical resistivity to decrease with increasing  
436 volumetric water content. The transition between high resistivity (dry period) and low  
437 resistivity (wet period) can be represented either by two different straight lines or by an  
438 exponential, as suggested by Russel et al. (2010), with measurements of gravimetric water  
439 content. To clarify this decrease, further measurements are currently being taken. Here again,  
440 it can be noted that the greater proximity of clusters 2 and 3, observed particularly on 27  
441 September 2010, would seem to indicate that these two clusters could well be classified as a  
442 single cluster.

443

444         **5. Conclusions**

445

446           Electrical resistivity tomography was carried out on an experimental site in order to  
447 determine the capacity of this method to locate fabricated defects and to characterise the  
448 heterogeneity of the cover material. The surveys, carried out at different periods in the year,  
449 showed that electrical resistivity tomography provided satisfactory results over almost the  
450 whole year. Detection of anomalies was easier when the inspection took place in a wet period  
451 and was more difficult, or even impossible, in a dry period. In favourable meteorological  
452 conditions, the 10 cm-wide crack which simulated an ageing defect was clearly identified  
453 with an inter-electrode spacing of 0.50 m. The heterogeneity of the cover material was  
454 demonstrated by each of the surveys in the wet period. Indeed, variations in electrical  
455 resistivity, once corrected for temperature, remain in the gravelly clay material, underlining  
456 the existence of different modes of behaviour. The multivariate analysis (ACH) carried out on  
457 the electrical resistivity of the cover material for the different dates of measurement permitted  
458 the establishment, first, of four resistivity-homogenous clusters, perceptibly distinct by  $2 \Omega.m$   
459 in the wet period; and secondly, putting the ERT model blocks into clusters highlighted the  
460 spatial organisation of the cover's heterogeneity. Finally, a combined analysis involving  
461 geotechnical measurements (water and fines content) and modalities of compaction showed  
462 that they were linked to the statistical characteristics of the clusters. In addition, the  
463 monitoring, over time, of electrical resistivity as a function of the volumetric water content  
464 showed that resistivity increased as soil humidity decreased; this increase was more rapid  
465 when the measurements were made in dry periods.

466           The heterogeneity of the material forming landfill cover is thus an important parameter  
467 to be taken into account when establishing the cover. However, while the permeability of the  
468 cover material depends mainly on its particle size, it also depends on its state of compaction.  
469 Particular attention must be paid to establishing the cover on landfill sites so as to ensure good

470 tightness over time. This study has shown that the use of electrical resistivity tomography can  
471 allow the characterization of the heterogeneity of the cover. The monitoring, over time, of  
472 electrical resistivity has also shown that the state of the soil in dry periods, with the  
473 appearance of cracks in the gravelly clay material, jeopardizes the tightness of the cover in  
474 these periods. Nevertheless, the closing up of cracks in wet periods was observed, both  
475 visually and by tomography. These observations lead us to recommend the use of electrical  
476 resistivity tomography in wet periods, which favour the detection of defects. Also, to avoid  
477 cracking in the cover material, it would be useful to sprinkle the cover in dry periods so as to  
478 limit the appearance of zones liable to water infiltration.

479

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481

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486

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## FIGURES

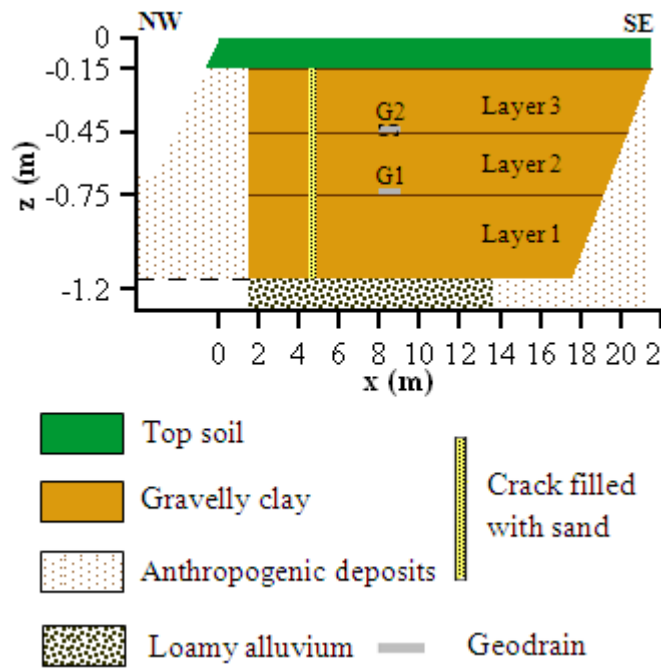


Figure 1: Section of the experimental site

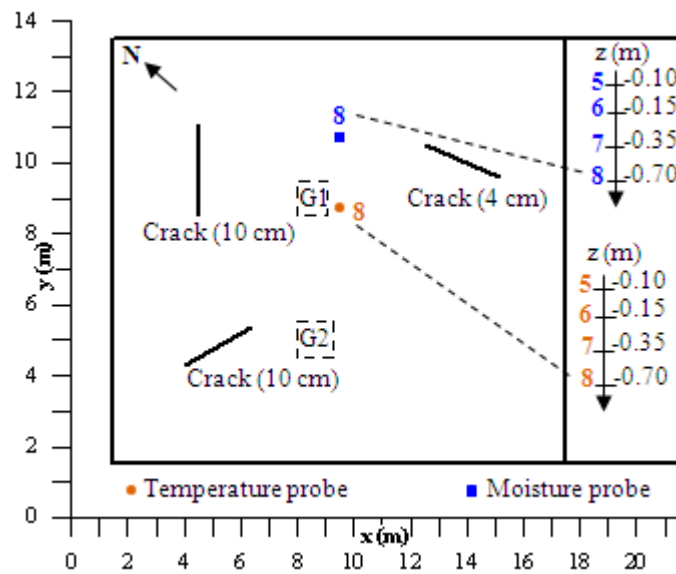


Figure 2: Location of defects intentionally made and probes in the experimental site

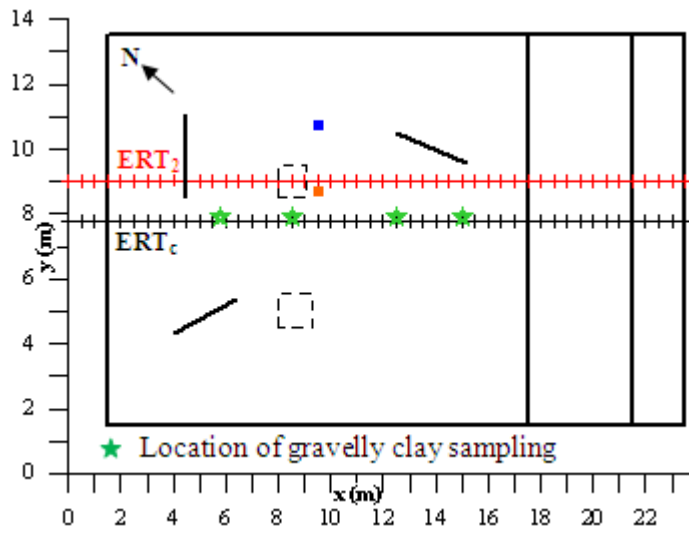
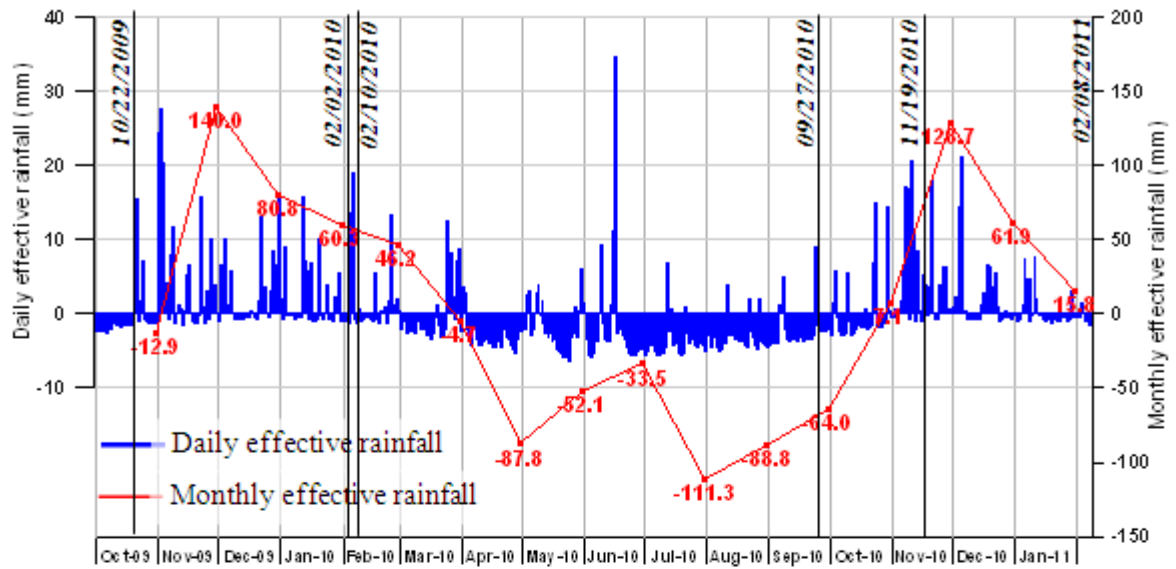
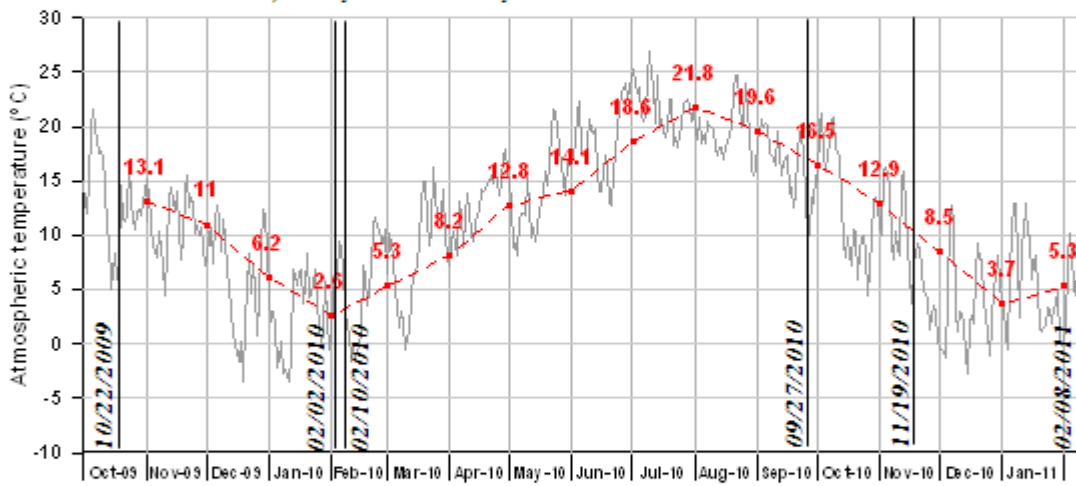


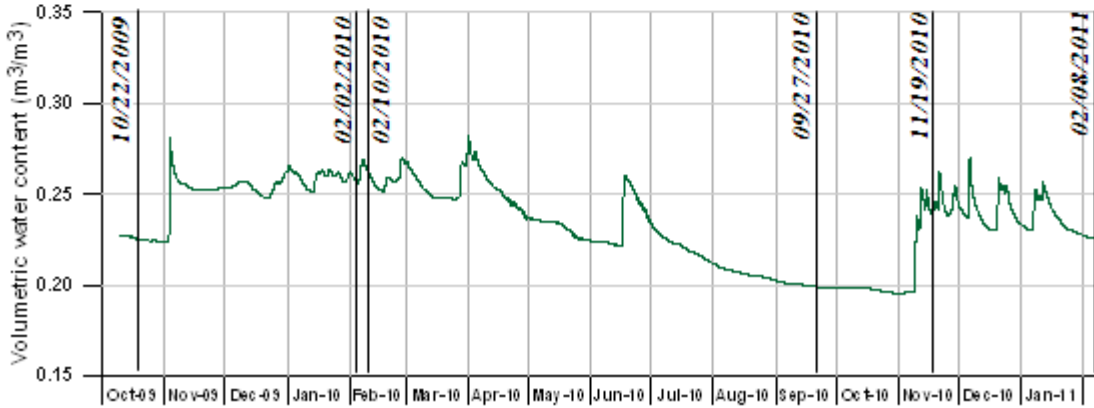
Figure 3: Location of electrical resistivity tomography profiles on the experimental site



a) Daily and monthly effective rainfall



b) Mean daily and monthly atmospheric temperature



c) Volumetric water content at a depth of 0.70 m (probe n°8 in Figure 2)

Figure 4: Data for effective rain and atmospheric temperature near the experimental site and humidity data in the gravelly clay material (from October 2009 to February 2011)

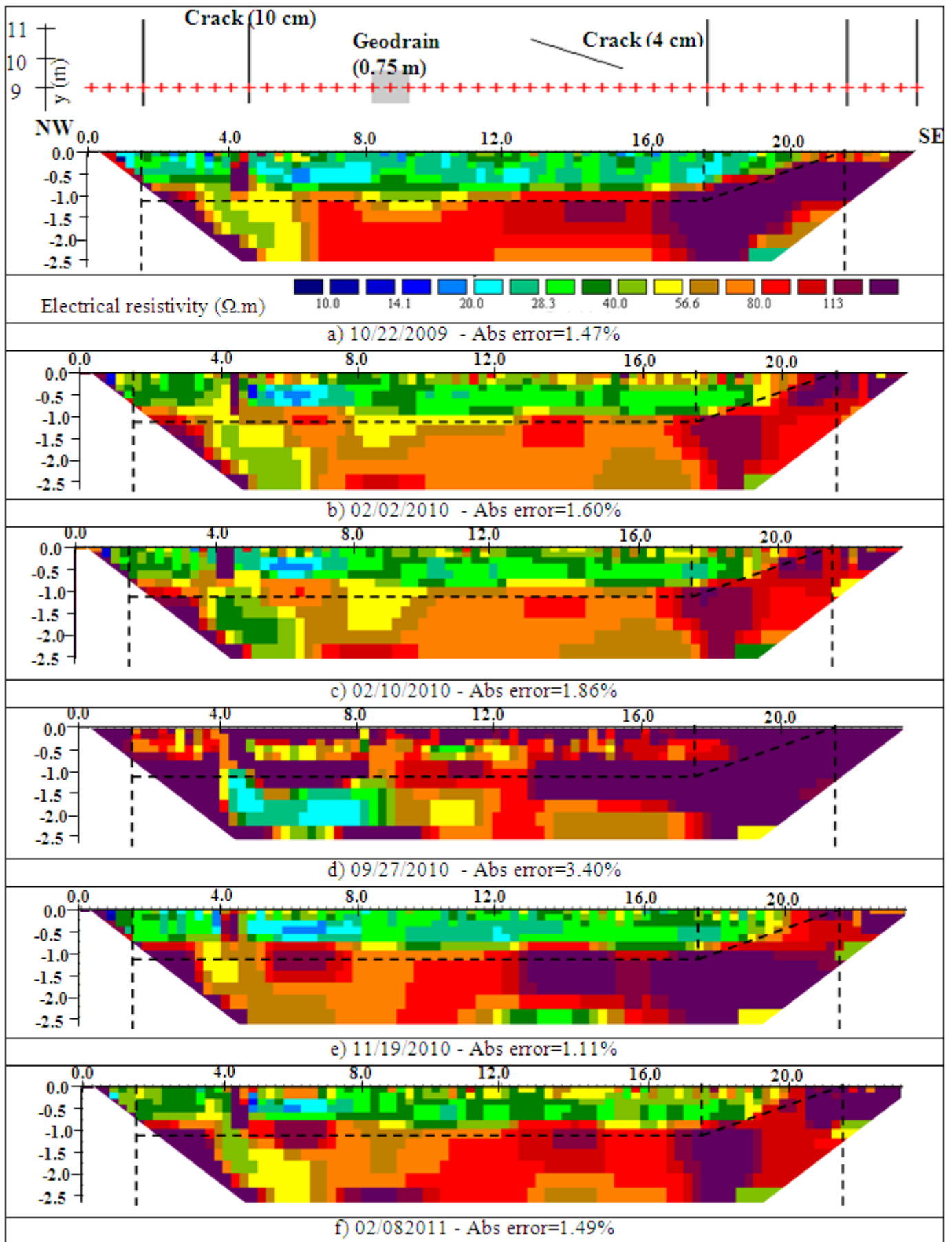


Figure 5: Models of electrical resistivity (not corrected for temperature) of ERT<sub>2</sub> profile after five iterations (model block cells)

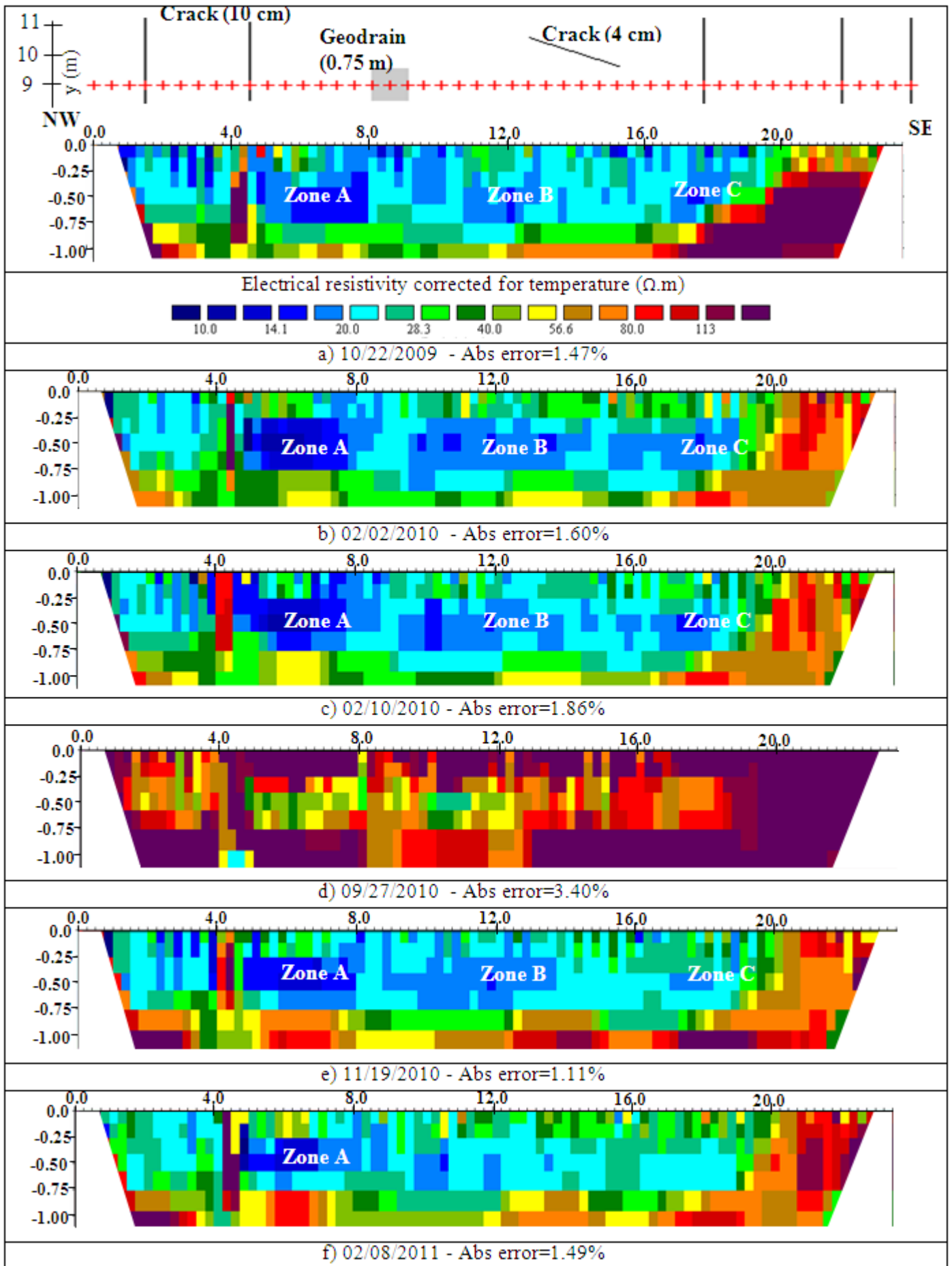


Figure 6: Models of electrical resistivity corrected for temperature in the cover along ERT<sub>2</sub> profile (model block cells)

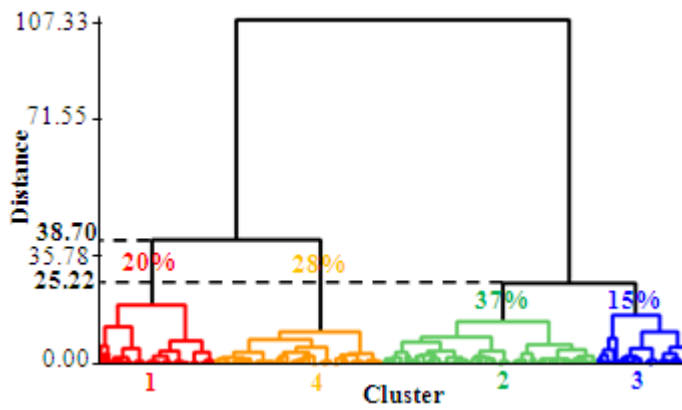


Figure 7: Dendrogram of the standardized variables of electrical resistivity corrected for temperature in the six surveys along ERT<sub>2</sub> with the percentage of blocks in each cluster

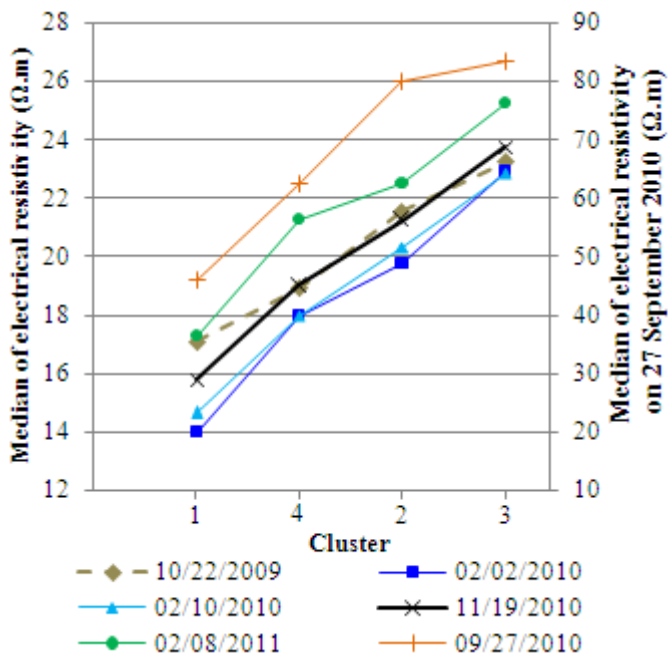


Figure 8: Median of electrical resistivity corrected for temperature, by cluster and date of survey

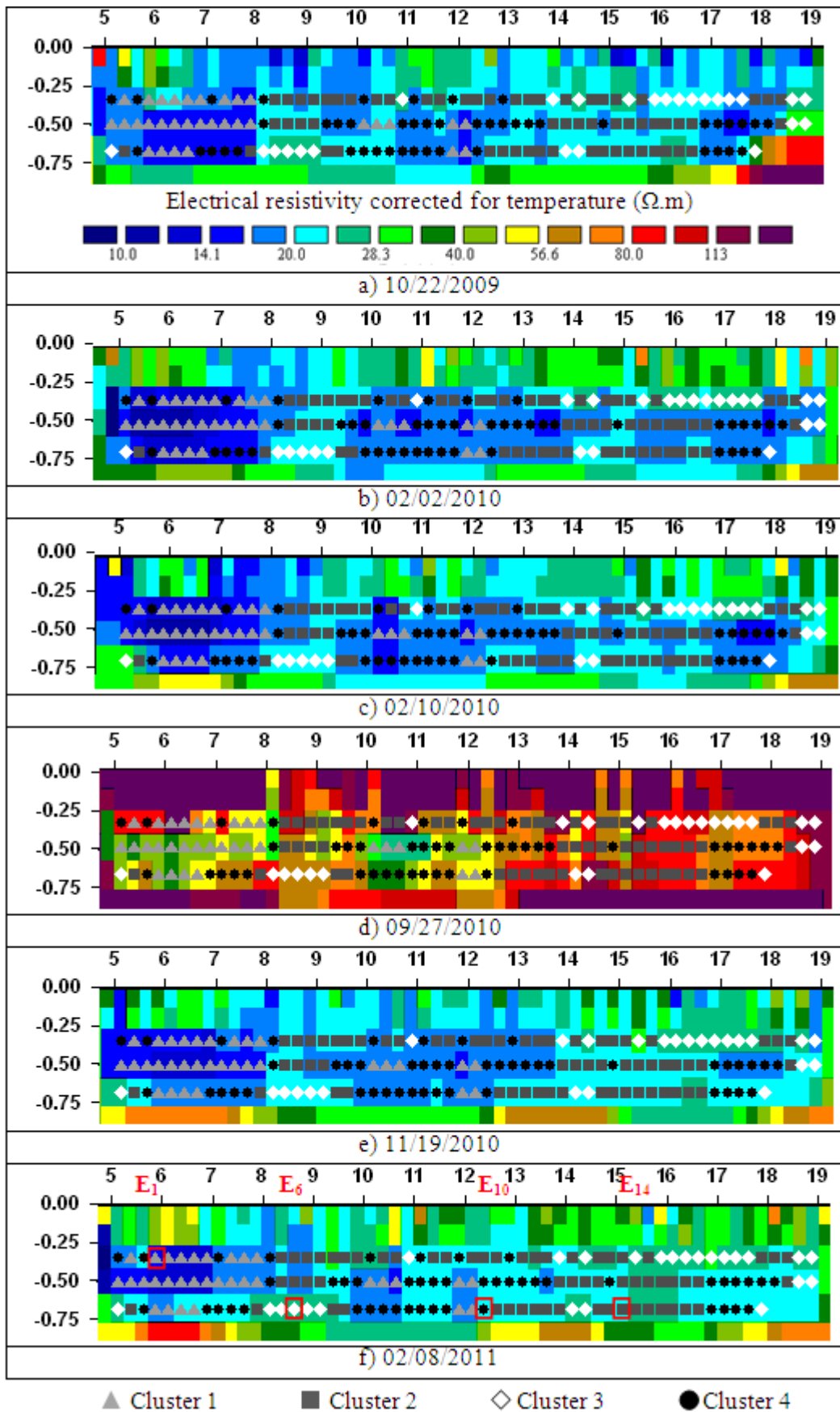


Figure 9: Spatial distribution of the clusters of electrical resistivity as determined by multivariate analysis along the ERT<sub>2</sub> profile



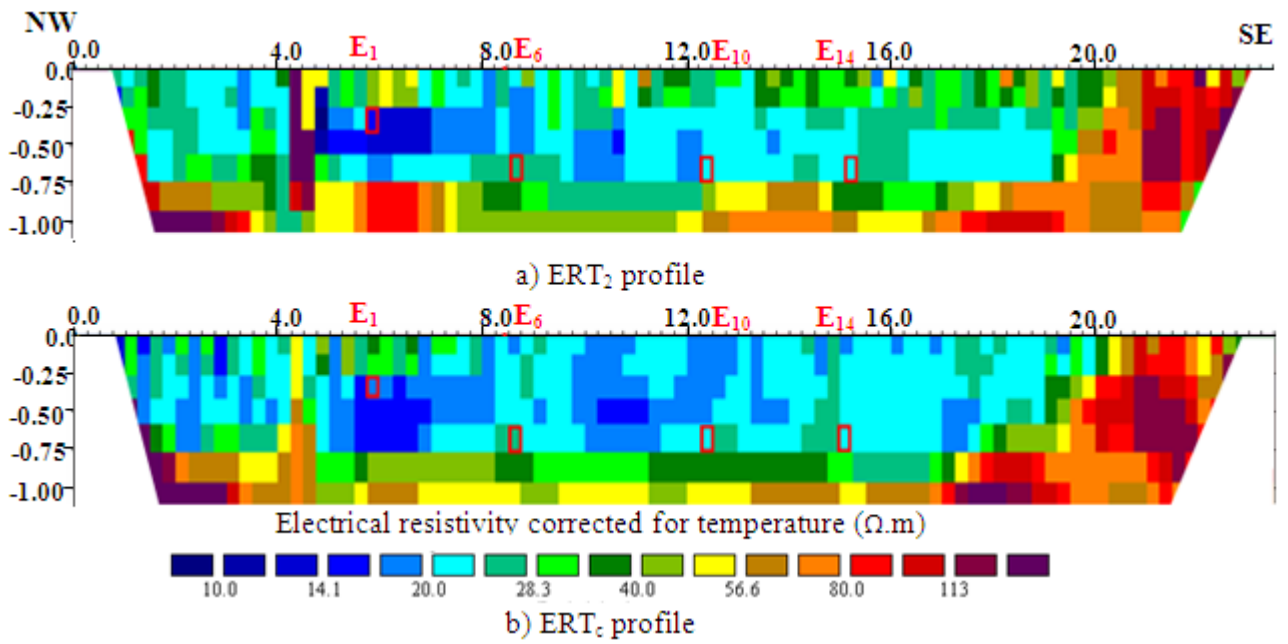


Figure 10: Models of electrical resistivity corrected for temperature in the cover on 8 February 2011 (model block cells)

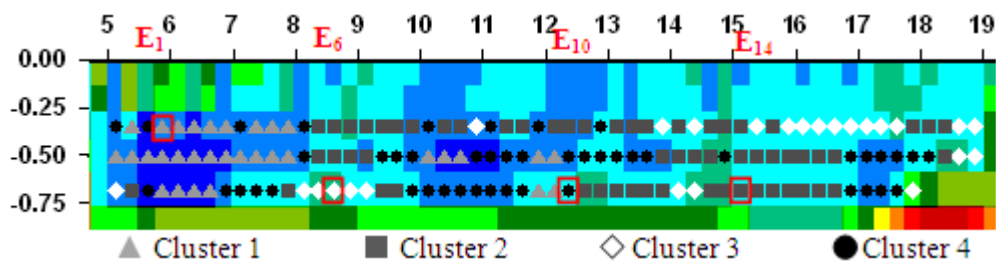


Figure 11: Spatial distribution of clusters of electrical resistivity established by multivariate analysis along profile ERT<sub>c</sub>

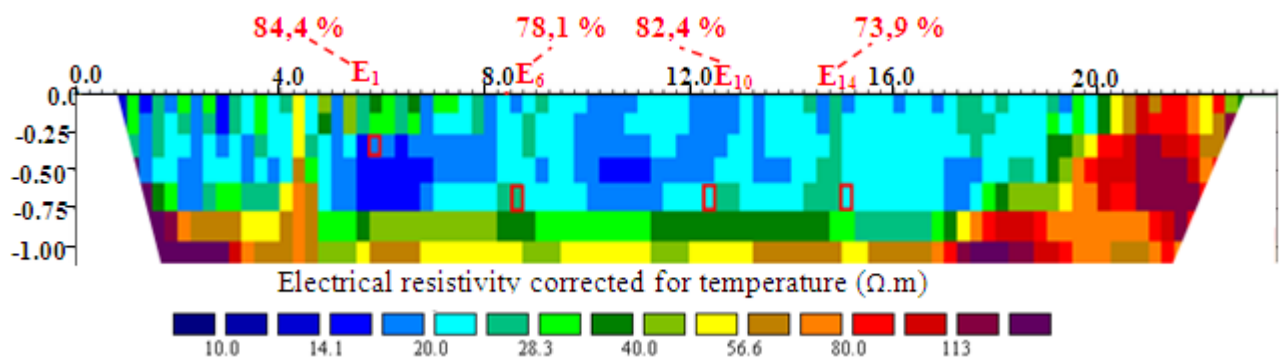


Figure 12 : Fines content of samples along ERT<sub>c</sub> profile

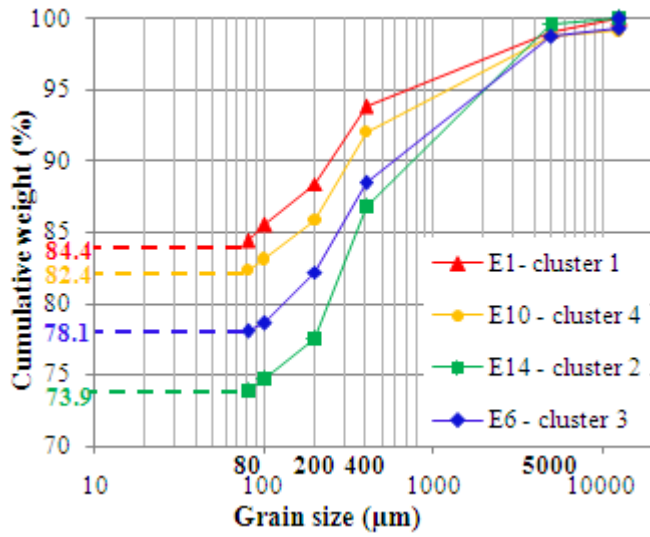


Figure 13: Particle-size distribution curve for the samples taken

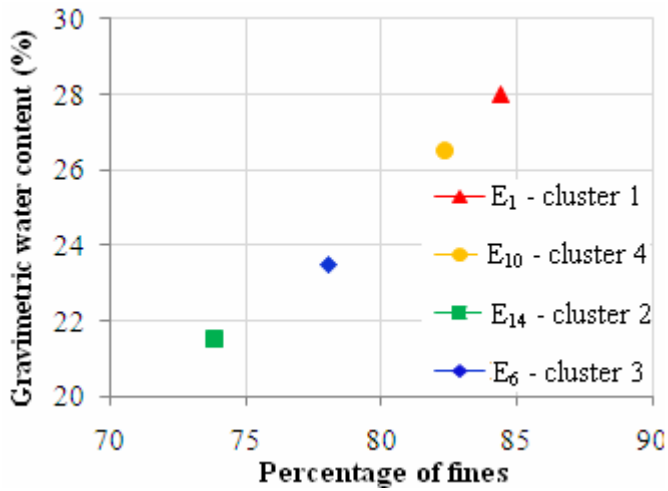


Figure 14: Percentage of fines as a function of the gravimetric water content for the four samples

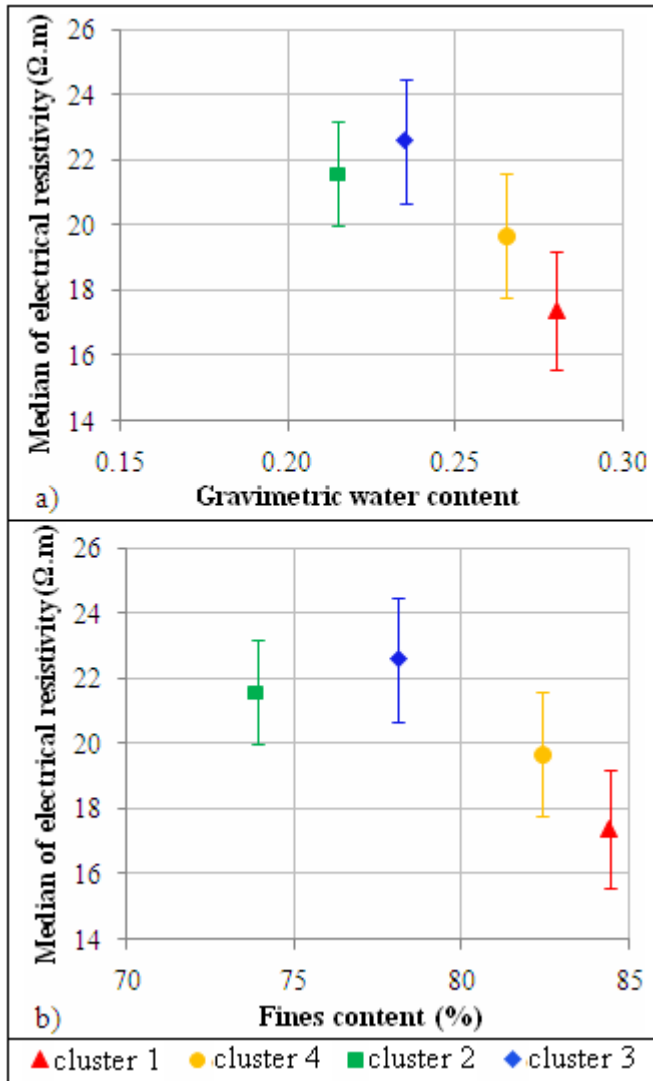


Figure 15: Median of electrical resistivity for the four clusters of  $ERT_c$  in relation to the gravimetric water content (a) and the fines content (b) of the four samples of loamy-clay material

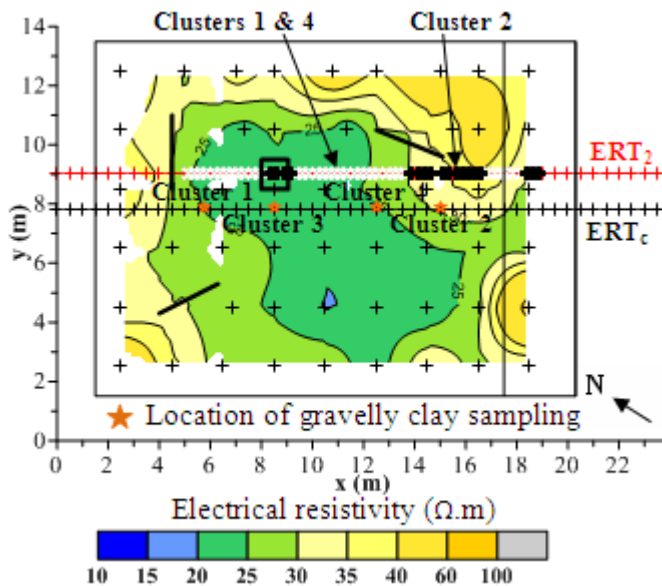


Figure 16: Map of resistivity corrected for temperature on the surface of layer 2 of the gravelly clay material (depth of 0.45 m)

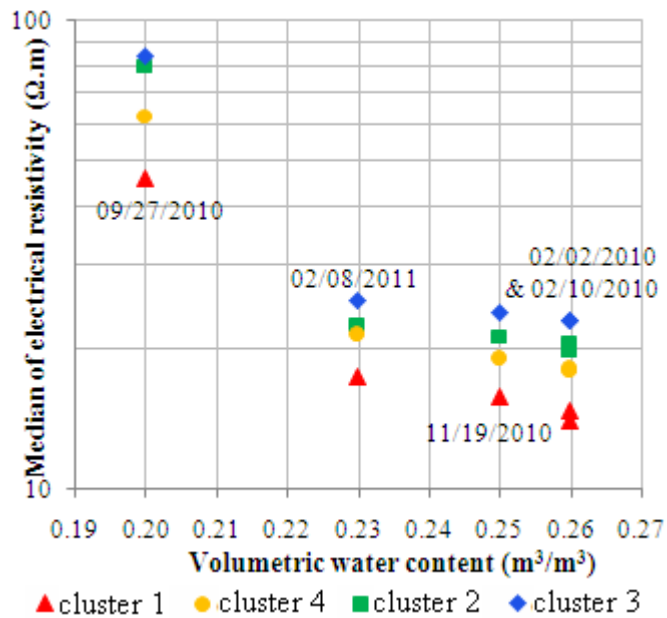


Figure 17: Median values of electrical resistivity of the four clusters of ERT<sub>2</sub> as a function of the volumetric water content at a depth of 0.70 m during the five surveys